CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

There are many articles [1-5] in literature featuring various SOFC stack and design, fabrication, SOFC performance and its applications. Most of these studies report higher efficiency and pollution free operation of SOFC technology. Extensive research is in progress on efficiency improvement of SOFC systems alone under various design and operating conditions. Successful development and operation of the Westinghouse tubular SOFC based cogeneration system proved the suitability of an SOFC system for combined heat-and-power (CHP) application in the hybrid mode [6, 7]. This further boosted the research and development on modeling and simulation of many hybrid schemes involving SOFC system. Many hybrid SOFC systems modeling have been proposed and available in the open literature. Various studies performed with the help of such models include configuration analysis, parametric sensitivity analysis, energy and exergy analyses, performance analysis at off design/part load condition, dynamic/transient analysis, feasibility studies, economic analysis and optimization studies.

In this chapter, comprehensive literature surveys on SOFC integrated hybrid gas and steam turbine based power systems are discussed. These systems are categorically described based on their configuration and the purpose of analysis. The results of the previous analyses done on SOFC hybrid systems are discussed for comparison, assessment of performance and improvement. Finally, the scope of the present study is highlighted at the end.

2.2 HYBRID SOFC–GT systems

2.2.1 Configurations and parametric analysis

A large number of hybrid SOFC–GT system models with different configurations are available in open literature. With the help of such modeling one can predict the overall performance of the SOFC–GT hybrid scheme. The various system components which are individually modeled and then integrated into the hybrid scheme include the air and fuel compressors, the recuperators for air and fuel preheating, pre-reformer or internal reformer, the SOFC, the combustor or the after burner, the GT, the heat recovery steam generator (HRSG), CO_2 capture etc.

Palsson *et al.* [8] proposed an SOFC–GT system with 30% fuel reforming in an external pre-reformer with anode gas re-circulation where the effluent from the anode was partially recycled to supply steam and heat to the external reformer. The rest of the anode effluent was burnt in the combustor with the cathode effluent. The hot gases were then sent to the GT for generating additional electrical power, whereas the exhaust gas from the GT was utilized for fuel preheating. They performed a parametric sensitivity analysis for the hybrid SOFC–GT system to understand the influence of various operating parameters such as cell voltage, pressure, air and fuel flow rate, air and fuel inlet temperature on SOFC performance. They observed that cell efficiency and its fuel utilization factor increases at higher operating pressure. Increase in air temperature also enhances the fuel cell efficiency and fuel utilization. However increase in fuel inlet temperature has very little impact on fuel cell efficiency, fuel utilization. While keeping the air flow constant, when they varied the fuel flow rate, they observed a direct proportionality between fuel cell electrical efficiency and fuel utilization and also the highest fuel utilization occurred at a lower fuel flow. They also observed similar pattern of efficiency variation and fuel utilization with increasing air flow at constant fuel flow rate. When air flow rate to the fuel cell increases, it enhances cell cooling and hence the cell temperature and the fuel cell current density decreases. They also analyzed the influence of these operating parameters on the hybrid SOFC–GT system performance. The compressor pressure ratio (CPR) was found to be the most notable parameter having large impact on the hybrid system performance. Hybrid SOFC–GT system would be economically feasible only at higher CPR because at lower CPR, the GT would produce negligible power and the system would be equivalent to a standalone SOFC only. They investigated the hybrid cycle also with inter-cooling of air compression and GT reheat and found very little gain in performance, especially with the reheat case.

Anode gas recirculation is usually performed by means of an ejector and through this; the use of an expensive HRSG can be avoided [9]. However, for providing the steam required initially during start-up, the plant might require an external boiler or a HRSG. Hence, an SOFC–ST/SOFC–CC is a more viable and economical option from this point of view. But otherwise also, it is possible to analyze the system without the HRSG, without taking into account the start-up dynamics. Modeling of start- up dynamics requires a more detailed transient model of all system components. The plant simulation without the external boiler was done by Calise *et al.* [9] considering that initially the fuel is channeled to the combustor and the GT bypassing the SOFC and steam is produced by utilizing the heat of the GT exhaust gas. This steam is then mixed with the fuel before it enters the SOFC stack that activates the fuel reforming. When the reforming reaction is fully activated, the electrochemical reaction would generate the steam required for the reforming reaction and the external boiler can be disconnected upon reaching the desired value of steam to carbon (S/C) ratio in the simulation. S/C ratio is defined as the ratio between the number of the H_2O molecules and the number of the C-atoms of fuel components and is an important parameter in SOFC system simulation. The calculation of fraction of anode gas stream, required to be recirculated, is done on the basis of fulfillment of the desired value of S/C ratio. The most usual value of S/C ratio taken in analysis varies between 2 to 2.5. An increase in S/C ratio means an increase of the molar flow ratio between the fresh and the recirculated fuel which would demand for higher fuel pressure to sustain the anode gas recirculation [10]. This is acceptable because the fuel compressor can be used to increase the fuel pressure and also at higher S/C ratio the problem of carbon deposition at the anode is avoided.

Cunnel *et al.* [11] analyzed six different hybrid cycles in order to have clear understanding of the various integration schemes and to determine the theoretical optimum configuration thereof. These were namely (i) the FC schematic where the fuel cell replaces the combustor of a simple gas turbine (SGT) schematic, (ii) the SGT–FC cycle with both fuel cell and combustor in the cycle (iii) the recuperated gas turbine (RGT)–FC schematic with a recuperator between the compressor and the fuel cell (iv) intercooled recuperated gas turbine (IRGT)–FC schematic with an intercooler between the compressors (v) IRGT–reheat FC schematic with one reheat fuel cell between the high and low pressure GT (vi) IRGT–FC–reheat FC cycle with one primary fuel cell between the recuperator and the combustor and one reheat fuel cell. Variation of thermal efficiency and net specific power variation with compression ratio was reported for all these cycles for the purpose of comparison with the corresponding cycle without the fuel cell. It was shown that both the thermal efficiency and the net specific power were higher for the hybrid schemes compared to their corresponding without the fuel cell. The maximum thermal efficiency (76.4%) was obtained in case of the IRGT–FC–reheat FC cycle, however this cycle was recommended as impractical because the efficiency was peaking at a low compression ratio with minimum specific power and for that matter, the size of the turbine for a given mass flow rate will be too big. Specific power was found to be higher at higher pressure ratio. In case of the RGT–FC cycle, thermal efficiency of 64.1% was achieved at a pressure ratio of 14 with reasonable specific power of 520 kWs/kg. With addition of the intercooler, efficiency further increased to 69.6% and there was considerable increase in specific power as well, however it occurred at a pressure ratio of 30. Therefore, IRGT–FC system was shown as a strong contender which provided an optimal solution for the hybrid scheme. The maximum thermal efficiency and net specific power both occurred at high compression ratio for this scheme.

Chan *et al.* [12] considered a hybrid SOFC–GT system consisting of an internal reforming SOFC stack, a combustor, a GT, two compressors (fuel and air) and three recuperators for the purpose of air and fuel preheating and also water heating at the end. The recuperators viz. the air recuperator (AR), fuel recuperator (FR) and a water heater were placed sequentially one after the other and the GT exhaust was the heat source for recuperation. The effect of a pressure and fuel flow rate on the performance of the components and the overall system was investigated in their study by varying the operating pressure from 5 to 9 bar and fuel flow rate from 14 to 16.5 kmol/h. It was found that the overall system efficiency increases with increasing pressure, but when the fuel flow rate is increased, keeping the fuel utilization factor constant, it does not lead to any improvement in system efficiency, rather the efficiency decreases slightly. Although there was marked improvement in SOFC stack and the GT power output at increased fuel flow rate, but increase in fuel consumption overweighed these advantages and resulted in lower system efficiency.

Selimovic and Palsson [13] analyzed the impact of networking (staging) of the SOFC stacks on hybrid SOFC–GT system performance and design. They observed a power increase of 2.7% and 0.58% respectively for the hydrogen (H_2) and 30% pre-reformed methane fuelled stand alone SOFC stack when it is staged into two smaller stacks in series. Further it was concluded that with staging of fuel cell stack, there is smaller variation of Nernst potential across fuel cell area of each stage which causes a more uniform distribution of current density within the fuel cell. Hence it helps in reduction of the fuel cell polarization losses. For the SOFC–GT hybrid cycle, two arrangements of networking were considered for investigation. In the first, both the fuel (natural gas) and air flow stream was arranged in series (Network A) and while in the second option, the fuel stream was arranged in series and the air stream in parallel (Network B). Both the networks A and B were investigated with a total stack area equal to the area of the single stack, which was used as reference for performance comparison. The total number of cells in the single stack was 15000 while it was equally divided into two staged networks (network A and network B). Considerable performance improvement was observed for network A with 7.48% improvement in total power (SOFC and GT power) and 7.77% increase in efficiency. This was attributed to effective thermal management with improved cell cooling and uniform temperature profile that caused reduction in required air flow and increased fuel utilization in the stacks. For the network configuration B, the impact of dividing airflow on performance was negative; efficiency decreased by 2.48% and the total power by 2.5%. In this case, air flow requirement increased due to insufficient cell cooling resulting from parallel air flow and fuel utilization reduced, leading to decrease in the SOFC power. It was concluded that networked stacks with relatively smaller stacks reduces the cooling demand of the cells and thus make it a better choice.

Kuchonthara *et al.* [14] evaluated combinations of SOFC and several enhanced GT cycles *viz*. the steam injected gas turbine (STIG) cycle, GT–ST combined cycle and the humid air turbine (HAT) cycle. In a STIG system, the steam generated in the HRSG using the GT exhaust is directly injected to the combustor and simultaneously expanded in the GT together with combustion gases and air streams. In a HAT cycle, the air is humidified by addition of water vapor in a humidifier prior to entering the SOFC cathode. Simulation was performed considering hydrogen fuel and working pressure ratios of 5, 7, 10 and 15. A constant air utilization factor of 0.3 was chosen while the fuel utilization factor was varied between 0.45 and 0.95 in order to obtain TIT values in the range from 1000 to 1700 K. TIT increases with a decrease in fuel utilization factor. Finally the effects of TIT and GT operating pressure ratio on thermal efficiency and specific work of the overall system were assessed for all these hybrid SOFC cycles. SOFC–STIG system was presented for two cases e.g. the simple SOFC–STIG system and the system with an air pre-heater (APH). In the second case, the GT exhaust besides being used for generating steam in the HRSG was also used to preheat the compressed air stream. In case of the SOFC–HAT system, it was observed that the thermal efficiency rises up with the TIT at a given pressure ratio. This was due to enhanced energy recuperation and improvement in GT efficiency with increasing TIT that overcome the negative effect of decrease in fuel utilization at higher TIT. Specific work also showed an increasing trend with TIT for this system. The system efficiency however decreased with increase in pressure ratio at a given TIT. While comparing the results of all the four systems, the SOFC–HAT system was found to be the most efficient cycle with the highest thermal efficiency and specific work output especially at the condition of high TIT and pressure ratio. At low pressure ratio however, the specific work was the lowest for this system.

The same authors in a different study [15] while investigating the effect of steam recuperation (SR) on overall efficiency of a SOFC–STIG system found that the overall efficiency of system with heat and steam recuperation was higher than the system with only heat recuperation. Heat recuperation here means the preheating of air and steam recuperation refers to steam generation in the HRSG by utilization of GT exhaust gas heat. For the simple SOFC–STIG system, the overall thermal efficiency was shown to be decreasing with increasing TIT (decreasing fuel utilization) at all pressure ratios. The specific work however increased with TIT at a given pressure ratio, because at higher TIT, the system produces more steam and injection of relatively higher steam quantity through the GT causes an increase in the net specific work. Again at a given TIT, thermal efficiency was shown to be improving with pressure ratio while the specific work was not changing. Keeping TIT constant when pressure ratio is increased, it reduces both the GT exhaust temperature and the amount of steam generated in the system. Less amount of heat is required to heat the steam in the combustor and hence the efficiency increases. For the SOFC–STIG system with the APH, however, the efficiency increased with increasing TIT for all the pressure ratios except for 5 where an opposite trend was observed. Further it was observed that at low TIT, efficiency decreased with pressure due to reduction in fuel utilization factor while the trend was opposite at high TIT due to substantial improvement in GT efficiency at increased pressure. Specific work output which was independent of pressure ratio in the simple SOFC–STIG system was found to be increasing with pressure ratio for the system with APH.

Stiller *et al.* [16] developed a 2-Dimensional planar and a 1-Dimensional tubular SOFC model to simulate and compare a SOFC–GT hybrid cycle while investigating the effects of various parameters such as pressure ratio, air inlet temperature etc. on system performance. It was shown that the hybrid systems could achieve efficiency above 65% with both planar and tubular SOFC.

Lai *et al.* [17] proposed a new method to evaluate the performance of SOFC–GT hybrid cycle but without using an actual SOFC. The SOFC was replaced by a furnace to simulate fuel cell off-gas condition in order to avoid the high cost involved with SOFC. With this assumption, a reasonably approximate simulation of a real SOFC–GT behavior was done and it was made possible by them.

Park *et al.* [18] analyzed the influence of steam injection on performance of a pressurized and an ambient pressure SOFC–GT system separately and observed GT power augmentation with steam injection. They found that the effect of steam injection on system efficiency was different for systems with different configurations and design conditions. The power augmentation increased with increasing TIT in the pressurized system, while it was almost constant in the ambient pressure system. Further, the power boost was greater for higher GT pressure ratio design (pressure ratio 8.5) in both the pressurized and ambient pressure systems. They considered two GT pressure ratios in their study viz. 3.5 and 8.5 representing one micro GT and a medium size GT respectively. It was found that the advantage of steam injection on system peak efficiency was minimal in the pressurized system, while in the ambient pressure system, the steam injection provided a considerable efficiency improvement for the high pressure ratio design.

Gorla *et al.* [19] presented the thermal efficiency and net specific power variation with compression ratio for a recuperated hybrid SOFC–GT system and compared these parameters for the system without SOFC. Both the thermal efficiency and the net specific power were significantly higher for the SOFC integrated system for all the compression ratios ranging from 2 to 30. Further they conducted a probabilistic analysis of GT field performance considering various thermodynamic random variables such as compressor inlet temperature, cycle pressure ratio, SOFC output, GT inlet temperature, adiabatic efficiencies of the compressor and GT and effectiveness of the regenerator etc. A scatter of ±5 percent was specified for all these variables assuming normal distribution for all random variable scatters. The cumulative distribution functions (CDF) and the sensitivity factors were evaluated for both the overall thermal efficiency and net specific output response due to the uncertainties in the thermodynamic random variables. The sensitivity factor for the compressor adiabatic efficiency was found to be larger than the GT adiabatic efficiency. It was also observed that the sensitivity factors due to compressor adiabatic efficiency and inlet temperature influenced mostly the overall thermal efficiency while the sensitivity factor due to TIT influenced the most in the evaluation of the net specific power output.

Amati *et al.* [20] presented a thermodynamic model of a natural gas-fed SOFC stack integrated with a GT power generation system using an external reformer (30% pre-reforming). An HRSG was used in their schematic to generate the steam required for fuel reforming. From simulation, they obtained a system efficiency of about 59.3% at design conditions of CPR 11, GT expansion ratio 9.7 and TIT 1250 K against 53% efficiency of the stand alone SOFC. The results further showed a decrease in system performance with increasing TIT. They also investigated the effect of current density and oxygen utilization (constant fuel utilization) on efficiency. Both SOFC and system efficiency was reported to be less at higher current density. With increasing oxygen utilization however, the SOFC efficiency revealed an opposite trend, while the system efficiency was shown improving.

Chinda and Brault [21] developed a hybrid SOFC and GT system model, considering two specific configurations of the hybrid system for comparative analysis. In the first configuration, a fraction of the high temperature combustor exhaust was routed to the fuel heat exchanger to preheat the fuel stream while the air stream was preheated utilizing the GT exhaust gases. In the second configuration, both the fuel and air streams were heated by GT exhaust gases. For same inlet conditions, the performance of the first configuration was found to be superior with 58% cycle efficiency compared to 53.5% of the second configuration. This was attributed to high operating temperature in the SOFC stack achieved through fuel heating by combustor exhaust stream in the first configuration.

2.2.2 Steady state modeling and part load/off design performance

A power generation system usually performs better at the design condition, however depending on load, power requirement varies and therefore, evaluating system performance at off design conditions is necessary for practical point of view.

Costamagna *et al.* [22] presented the design and off design (part load) performance of a small size power hybrid system obtained by coupling of a recuperated micro gas turbine (MGT) and high temperature SOFC tubular reactor. In depth discussion on the design and off design performance of the hybrid system was presented in their work for constant fuel utilization. The hybrid system off design performance was analyzed for both fixed (85000 rpm) and variable MGT rotational speed control system.

At constant turbine speed, the off design performance was evaluated by varying the fuel flow rate to the hybrid plant. These part load simulations at constant rpm showed large variations in air utilization and loss of efficiency. The turbine inlet temperature (TIT) puts a limit on the hybrid system performance at constant speed. The efficiency was found to vary from 61% at the design point (TIT=1173K, current density =4450 A/m^{2,} oxygen utilization factor =0.32) to 56.4% at 70% of nominal power (TIT=1080K, current density =3410 A/m^2, oxygen utilization factor =0.24).

For the variable speed operation, while varying the MGT rotational speed from 65000-85000 rpm, both air and fuel utilization as well as the SOFC inlet temperatures could be maintained at a constant values in part-load operation with only a small penalty on system efficiency. The efficiency was higher than 50% even at 30% of the power at design point (TIT=1115 K, current density =1890 A/m^2, oxygen utilization factor =0.22). This was mainly attributed due to higher recuperator efficiency owing to reduced air flow rate.

Yang *et al.* [7] compared the part-load performance of a SOFC–GT hybrid system in three different control modes: fuel-only control, rotational speed control, and variable inlet guide vane (VIGV) control. In the fuel control mode, the part-load operation was achieved by reducing fuel flow against constant air supply, while in the other two modes, it was achieved through control of the air and fuel supply. At part load operations, they found the best system performance with the speed control mode. System performance was the worst for VIGV control mode, but still they recommended for its use in a large-scale hybrid system where the application of rotational speed control mechanism sometimes may not be applicable.

Campanari [23] suggested for reducing air utilization and current density to achieve part load operation at constant shaft speed with constant fuel utilization. This approach, together with SOFC and GT power, also causes reduction in TIT. To achieve part load operation at variable shaft speed, he suggested reducing air flow rate and current density for maintaining constant air utilization. This however, leads to increase in turbine outlet temperature and therefore, it would require further reduction in current density to maintain a constant TIT in the system.

Kimijima and Kasagi [24] also made a comparison between variable and fixed shaft speed operations of a hybrid SOFC–GT system. They also found favourable part-load operation with variable speed with the reservation that the higher turbine outlet temperature is a concern.

Chan *et al.*[25] implemented a method of load shifting from the SOFC to the GT as a means of achieving part load operation. This would however demand fuel and air supply directly to the combustor bypassing the SOFC and hence system efficiency would reduce significantly in this method.

Pålsson and Selimovic [26] used shaft speed variation for studying part load operation of hybrid SOFC–GT system. For maintaining a constant TIT, they used an air heater/cooler before the SOFC to meet the requirements of air inlet temperature at part-load operation. They observed more power production from the SOFC at part-load operation with increased fuel utilization and low GT part-load efficiency.

Thus, from the above review, it is seen that fuel flow, air flow and their utilization, turbine shaft speed, SOFC temperature and TIT are the important parameters in part-load operation of SOFC–GT systems. Maintaining a constant temperature in the SOFC is very crucial to avoid thermal cracking, but achieving this, might be difficult with variable speed at low pressure as indicated in some of above studies.

2.2.3 Dynamic/transient analysis

Modern power plants are designed such that they quickly respond to sudden change in load and hence, power system simulation under dynamic/transient condition is of practical interest. During load change, the way in which a system proceeds from one operation point to another is determined by the system control strategy. Dynamic/transient system modeling helps to find a suitable system control strategy, however they are more complex than the steady-state models. Stiller *et al.* [27] presented a detailed dynamic model for a SOFC/GT hybrid system. They investigated both steady state and dynamic behavior of the system at part load condition. The steady-state behavior was first obtained in the form of performance maps to select an appropriate operation line. Next, the control objectives and the influencing disturbances were discussed with the main focus on a constant SOFC temperature under all conditions. The design of a combined feedback-feed forward control system layout was proposed and discussed. The system responses under load change, change in ambient condition, external disturbances as well as malfunction and degradation incidents were investigated. Various strategies were adopted for controlling power, fuel utilization, air flow, mean cell temperature. Controlling of power, fuel utilization and air flow was done by manipulating respectively the SOFC current, fuel flow, air flow and the generator power. The mean temperature in the SOFC was controlled by measuring the fuel temperature at SOFC exit and correcting the air flow set point. The set points of the air flow and the temperature were calculated on the basis of steady-state characteristics at constant fuel cell temperature operation.

Stiller *et al.* [28] performed one more similar study on a SOFC–GT hybrid system for investigating the dynamic behavior of the system on rapid load changes. The strategies of manipulating fuel flow for dynamic controlling of power were discussed and the system operation was found to be safe as it very quickly adapts to a new set point during a sudden load change.

Thorud [29] performed a dynamic analysis for a SOFC–GT system by simulating load change according to three different strategies viz. (i) load change at constant mean fuel cell temperature, (ii) load change at constant TIT and (iii) load change at constant shaft speed. The first strategy was found to be the most rapid load change method with the lowest degree of thermal cracking, uniform fuel cell temperature distribution, and the lowest current density at part load. Thus, it had the lowest risk with respect to system malfunctions and degradation. It also facilitated highest efficiency at part load operation. The constant TIT strategy on the other hand led to unstable operation at low load. The slowest response to load change was found for the constant shaft speed strategy and hence it was not found suitable for large load variation.

2.2.4 Energy and exergy analyses

Energy analysis, based on first law of thermodynamics, is a common and useful method of evaluating thermodynamic performance of any energy/thermal system. Most of the studies on hybrid SOFC–GT systems described in the previous section were specific to energy analysis where mainly the efficiency and specific/net power are determined and sometimes, the effect of the design/operating parameters on system performance are investigated through parametric study. First law based energy analysis does not explicitly identify those processes within the system that cause unrecoverable degradation of the thermodynamic state of the working fluid. Therefore, often exergy analysis is done because this is the method which is mostly used for evaluating inefficiency or exergy destruction of systems and processes. Moreover, system analysis together with the help of energy and exergy gives a complete overview of the system performance characteristics. The following are some studies specific to exergy analysis of SOFC–GT hybrid systems.

Calise *et al.* [9] presented on both partial and full load exergy analysis based on modeling of a hybrid SOFC–GT power plant consisting of an air compressor, a fuel compressor, several heat exchangers, a radial gas turbine, mixers, a catalytic burner, an internal reforming tubular SOFC stack, bypass valves, an electrical generator and an inverter. The part load/off-design operation was achieved through three different strategies as shown below.

Strategy A: Constant air flow rate, variable fuel flow rate, no combustor bypass;

Strategy B: Constant air fuel ratio, no combustor bypass;

Strategy C: Constant air flow rate, variable fuel flow rate and combustor bypass.

The plant simulation results were shown specifically for the full load operation. At full-load, the plant's electrical, thermal and exergetic efficiency were found to be 65.4%, 21.8% and 62.6% respectively. The catalytic burner and the internal reforming SOFC were the components that showed remarkable exergy destruction rate amongst all. The most efficient part-load operation was achieved with strategy B as it allowed for control of both the stack and GT inlet temperatures that helped in achieving simultaneously low cell over-voltage and high GT isentropic efficiency. On the other hand, a significant reduction of plant net electrical power production (35% of nominal load) could be achieved with strategy A, however electrical efficiency dropped down to 45% due to reduction in fuel air ratio. When the fuel flow rate is reduced to allow for reduction in plant net electrical power production keeping the air mass flow rate fixed, the fuel to air ratio decreases reducing both the TIT and the stack temperature. The SOFC and GT performance varies significantly at part load reducing the overall electricity produced by the hybrid plant. For the strategy C, the efficiency values were not showing any significant variation with respect to the other strategies. However they recommended that a better part load performance could be possible with the first criterion through proper optimization of the turbo-machineries design.

Bavarsad [30] made energy and exergy analyses of a methane-fed internal reforming SOFC–GT system with a pre-reformer, a SOFC stack, a combustor, a turbine, a fuel compressor, an air compressor, recuperators and an HRSG. Full load steady state plant simulation was done for exergy analysis and the results indicated that the SOFC, combustor and the pre-reformer were the most important sources of exergy destruction in the cycle. Additionally a parametric study was performed to evaluate the effect of fuel flow rate, air flow rate and pressure on the energetic and exergetic system performance. It was found that there was steady increase in both the first and second law efficiencies with CPR, however the second law efficiency was lower than the first law efficiency at all CPR. Increased fuel flow rate was found to have a negative impact on system performance because of increasing exergy destruction in system components. Air flow rate in general cooling affect in fuel cell stack and therefore has significant effect on TIT and SOFC stack temperature. The total power, both the first and second law efficiency decreased with increase of air flow rate.

Granovskii *et al.* [31] conducted energy and exergy analyses for two SOFC–GT systems, one with the provision of mixing steam with fuel (natural gas) and the other with anode gas recycling for fuel reforming. The steam in the first system was generated from water with utilization of GT exhaust gas. In the second system also, an HRSG was used but it was for steam generation required for driving the bottoming ST cycle. The power and efficiency of the SOFC stack in the two systems was taken to be the same for the purpose of comparison. This was made possible through reduction in input methane flow in the second system which together with the recycled methane, H_2 and CO provides the same energy content as in the first system. It was found that the scheme with anode gas recycling (second system) showed slightly higher energy and exergy efficiencies. The first scheme however was capable of producing more power. The authors recommended for implementation of the first scheme as it was more power intensive and there was about 20% reduction in fuel consumption, particularly at lower values of molar flow rate of oxygen and γ , a parameter that represents the fraction of oxygen utilized for fuel oxidization that takes part in direct energy conversion to electricity.

Haseli *et al.* [32, 33] examined the energetic and exergetic performance of a SOFC–GT plant with usual components but with the provision of only air preheating. Individual models were developed for each component, through applications of the first and second laws of thermodynamics to analyze the overall system performance. The simulation results showed that increasing TIT had a negative effect on the system's thermal and exergy efficiency while the net specific power was more at higher TIT. Higher TIT in the cycle was achieved through burning of additional fuel that was fed to the combustor bypassing the SOFC. Moreover, an increase in either the TIT or the CPR led to a higher rate of entropy generation in the plant. The combustor and the SOFC mainly contributed to the total irreversibility of the system, the individual share of each being equal to 31.4% and 27.9% respectively. The SOFC–GT plant was also compared with a traditional GT cycle with identical operating conditions. On an average, the hybrid plant showed 26.6% better exergetic performance than the conventional GT plant. The thermal efficiency was also higher by 27.8%. However, compared to the conventional GT plant, the rate of exergy destruction (irreversibility) was higher for the hybrid SOFC–GT plant over the entire range of compression ratios from 2 to 16.

Motahar and Alemrajabi [34] performed detailed steady state energy and exergy analyses of a SOFC–GT and a SOFC–STIG system with a steam injection rate of 0.134 per kg of air flow rate. The steam in the SOFC–STIG system was generated in an HRSG while anode gas recycling was done for fuel reforming in an external reformer in both the systems. Performance of the two systems was compared for fixed SOFC current density, voltage and stack temperature. It was found that the SOFC–STIG system performed better respectively with 17.87% and 12.31% more net power and thermal efficiency compared to that of the SOFC–GT system. The exergetic efficiency calculated for the SOFC–GT system was 58.28% while in the SOFC–STIG system; steam injection influenced positively with significant reduction in the exhaust exergy losses that boosted the system's exergy efficiency to 65.34%. However the overall system irreversibility was higher for the SOFC–STIG system by 16.98%. As usually, the combustor and the SOFC were found to be the major sources of irreversibility for the two hybrid systems. Additionally, they performed a parametric exegetic performance study for investigating the effects of CPR, current density and pinch point temperature difference (PPTD) of HRSG. With the increase in CPR, the exergy efficiency of both the hybrid systems was found to decrease, but this decrease was nominal for the SOFC–STIG system contrary to the SOFC–GT system. Exergy efficiency decreases with pressure because at elevated pressure, although the exergy output (system power) rises but simultaneously the fuel flow rate also increases and this increase in FFR is more dominant over the increase in exergy output. Further, the exergy efficiency was higher for the SOFC–STIG system over the entire range of CPR from 5 to 15 due to comparatively higher exergy output at increased pressure. With current density, the exergetic efficiency decreased again due to the dominant effect of increased fuel flow rate at higher current density, despite the increase in exergy output. The system irreversibility also increased gradually with current density due to growth of irreversibility in the SOFC. With the increase in PPTD (from 5 to 35 K), the steam injection ratio decreased and hence the exergy output also reduced. Due to increase in system exhaust temperature with PPTD, the external irreversibility also showed a gradually increasing trend.

2.2.5 Optimization studies

In the previous two sections, several discussions were provided on thermodynamic analysis on a number of SOFC–GT cycle configurations. Most of the above studies have confirmed hybrid SOFC–GT system as a potential candidate for high efficiency electricity production with low environmental emissions. However feasibility assessment, identification of the most interesting system design configuration and determination of optimal parameters for maximum possible performance demand use of optimization methods. Cumbersome parametric studies which are usually performed for selecting key system design and operating parameters can be avoided through optimization. System modeling combined with thermodynamic and economic optimization is an effective tool of any technological research as it indicates the feasibility and also provides ways to improve operational performance and efficiency of the best design configuration identified through optimization. Various optimization techniques that are used for system design and operating parameter optimization include conjugate-gradient method [35], particle swarm optimization (PSO) based parameter identification technique [36], seeker optimization algorithm [37], genetic algorithm (GA) [38], and non linear programming based on Quasi Newton algorithm [39]. Advanced methods such as differential evolution would also be suitable for such multi-objective combinatorial optimization problems. There have been few studies which have approached the design of hybrid SOFC–GT systems as an optimization problem.

Möller *et al.* [38] deployed a genetic algorithm (GA) tool to optimize the system parameters of a SOFC–GT system with and without a CO_2 separation plant. GA as an optimization tool is often used for handling multivariable highly non linear optimization problem. It is a powerful tool to handle strongly non-linear, noncontinuous, mixed integer optimization problems. The SOFC–GT system was configured with two SOFC stacks and a recuperated GT cycle. A fuel desulfurizer unit was put ahead of the pre-reformer and the pre-reformed fuel was equally split between the two stacks and fed to the anode in parallel while on the air side, the stacks were connected in series. In the SOFC–GT system with provision of CO_2-capture, the flue gas was cooled and dried in an exhaust gas condenser and the chemical absorption (mono-ethanolamine (MEA) absorbent) CO_2 separation modeling was done assuming the flue gas stream to be H_2S free.

In the optimization procedure, the electrical efficiency was selected as the objective function and the air flow, fuel flow (main and supplementary), cell voltage in the stack, air temperature at the stack inlet, reformer duty and pressure ratio were taken as decision variables. The maximum allowable SOFC stack temperature and TIT were used as constraints in the optimization while considering constant stack size. It was found that the SOFC stack temperature was the most influencing parameter. Low air flow, use of very little or no supplementary fuel in the GT combustor and a high degree of external reforming are some other factors that were found to be beneficial. The GA optimizer showed some difficulties using a combination of constraints and search intervals. They proposed for use of multipoint crossover in the mating process, high mutation rate, larger population size with narrowed search level, however all these would make the optimization process more time consuming.

For an internal reforming SOFC and intercooled GT hybrid cycle, Yi *et al.* [40], proposed a novel optimization strategy including a design of experiments (DOEx) approach. A humidifier was incorporated specifically in the system configuration to facilitate steam reformation of natural gas which also allowed for heat recovery from the low pressure GT exhaust. The DOEx approach helps optimizing the system operating parameters through determination of interactions among a large number of parameters that are important for overall system performance. This is otherwise challenging to examine in basic parametric analysis. The DOEx approach is based on determination of statistical significance of effects using detailed statistical analyses of variance where the parameters which are less significant are removed. Although it is usually applied to experimental parametric investigations; however the authors used this method for simulation results. A system electrical efficiency higher than 75% was achieved with this approach at a design pressure of 50 bar with 55% percent excess air in the SOFC.

Calise *et al.* [41] carried out design optimization of a hybrid SOFC–GT power plant using a traditional single-level approach in which the total life cycle cost-based optimal design of the hybrid plant was accomplished. The yearly overall plant cost which is the sum of the amortized capital cost, fuel cost and thermal energy savings was the objective function and the geometric and thermodynamic parameters were the decision variables. They also used GA considering the high level of complexity involved in optimizing a hybrid plant with strong non-linearity, large number of continuous and discrete decision variables. The initial population for the GA was set at four times the number of decision variables while the number of generations was set to a value of 700. The optimization gave an equally efficient system design configuration with much lower capital cost than that of the original configuration. The optimal results showed that the pre-reforming ratio, heat exchanger area and the SOFC active area are some among the many design variables that are most important for achieving high efficiency and low cost. Further they have advocated for coupling of GA and gradient based approach, the GA doing the general search of the optimization solution space and the gradient method helping narrow the search to a particular Kuhn–Tucker point or boundary.

Autissier *et al.* [42] presented a design methodology for a pressurized SOFC–GT hybrid cycle including an energy flow model, a heat and power integration model and a thermo-economic performance model for each subsystem. Energy flow model was developed for computing thermodynamic performance of energy conversion. The heat power integration model provided the base for design of the heat exchanger network and this was used for maximizing combined production of heat and power. Using the results of the above two, the thermo-economic model, determined the system performance, size and cost. The most attractive configuration was identified using an evolutionary algorithm multi objective optimization (MOO) approach integrated into OSMOSE, a Matlab based software specially developed for design and optimization of the integrated energy system. System optimization was performed to minimize the investment cost and maximize the system electrical efficiency. The S/C ratio, oxygen to carbon ratio, fuel processing temperature, fuel utilization, current density, TIT, air excess ratio, the system pressure were the decision variables. Optimization results showed existence of designs with costs ranging from 2400 $/kW with 44% efficiency to 6700 $/kW with 70% efficiency. Some other thermo-economic modeling studies of hybrid SOFC–GT plants are available in references [43, 44].

Zhao *et al.* [45] compared the performance of a simple indirect ambient pressure hybrid SOFC–GT system working under two thermodynamic optimization strategies; working either at maximum efficiency or producing maximum power output. First, the temperature dependent expressions for current densities corresponding to maximum SOFC power (i_p) and maximum efficiency (i_η) were derived following a differential approach. Finally the optimized power and efficiency of the hybrid plant were determined corresponding to i_p and i_η and then these were plotted against the fuel cell temperature for three different values (0, 0.001 and 0.002) of a parameter that represented the heat loss irreversibility from the fuel cell to the surroundings. It was shown that at maximum efficiency condition, the system runs at higher efficiency but with lower power density. The situation was just opposite for the maximum power condition. The results presented in their study were however more simplified in the sense that the configuration was based on a simple Brayton cycle, where the irreversible losses in the compressor and the turbine were not taken into account. Also pure hydrogen was considered as fuel instead of natural gas. But still the model was successful in giving a comparable prediction of the theoretical performance limit for the hybrid system.

Wu and Zhu [46] proposed an improved iterative PSO algorithm to optimize the operating parameters of a SOFC integrated micro GT hybrid system under various loads for different levels of power demand. The method which they used was a combination of an iterative method and the PSO algorithm where the discrete PSO was executed iteratively until the control profile converged to an optimal one and this was done in a Matlab environment. Dynamic optimization of parameters during load change is very important for optimal control of load changes. Calise *et al.* [41] also proposed for system optimization under part load condition as future scope of his work. The system optimized parameter could effectively track the output power with high efficiency in their improved method.

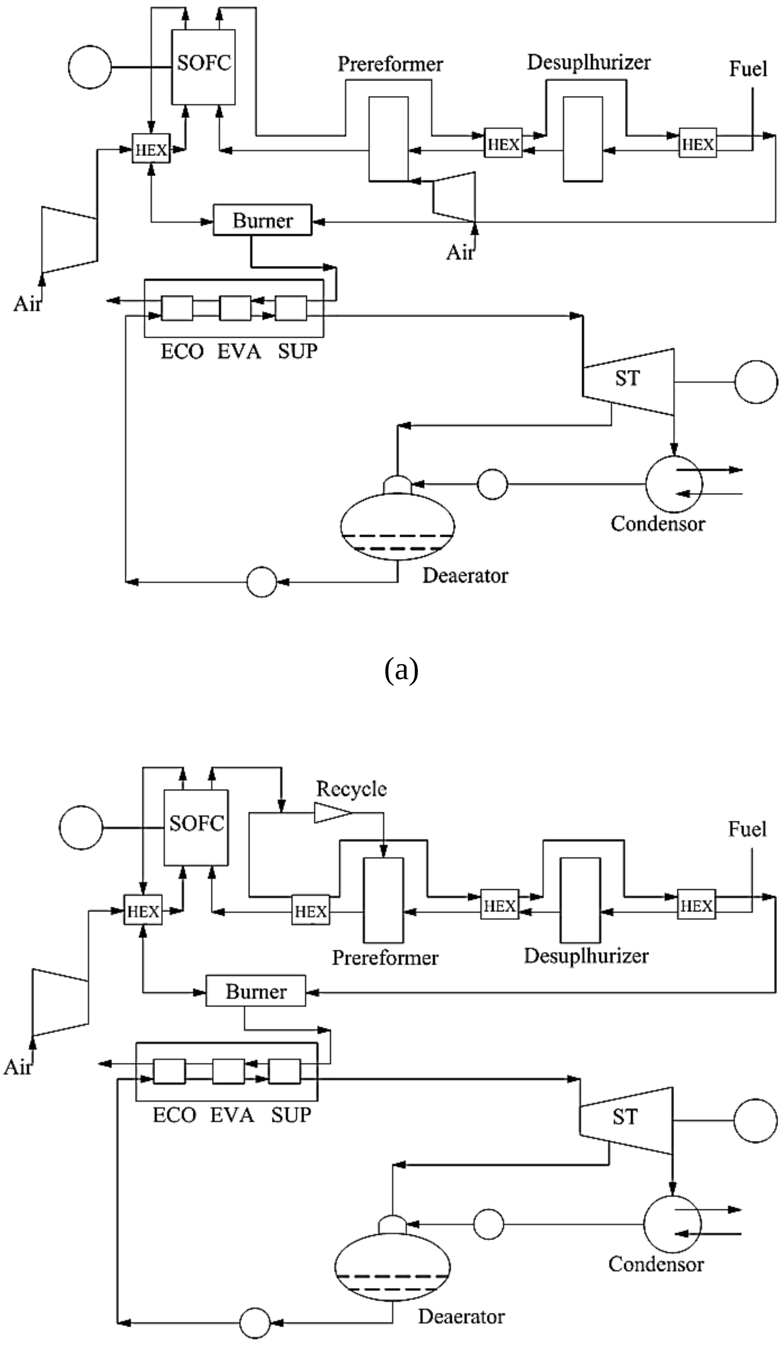
Baghernejad *et al.* [47] presented exergetic performance comparison and exergoeconomic optimization of three novel trigeneration systems viz. integrated SOFC–trigeneration, integrated biomass-trigeneration, and integrated solar-trigeneration plants. The study showed that the integrated SOFC–trigeneration system has the highest electrical exergy efficiency of 64.5% compared to 60% of the biomass based and 56% of the solar based system.

Hajabdollahi and Fu [48] optimized the performance of a cogeneration plant consisting of SOFC, GT, HRSG and an absorption chiller. The steam driven absorption chiller was used to provide inlet air cooling for the compressor of the GT plant. A GA based multi objective optimization application was used to find a number of operating and design parameters while simultaneously maximizing the exergy efficiency and minimizing the total cost rate of the cogeneration plant.

2.3 Hybrid SOFC–ST Systems

As discussed above, there are many studies available on analysis of SOFC–GT system while the investigations on combined SOFC–ST are very limited [49, 50, 51].

Rokni [49, 50] investigated a natural gas fired hybrid SOFC–ST system with the following configurations shown in Fig. 2.1 (a) and Fig. 2.1 (b). The topping cycle in Fig. 2.1 (a), consisted of an air compressor, an air pre-heater, the SOFC, a burner, a fuel desulphurizer unit, a catalytic partial oxidation (CPO) reformer and two heat exchangers for fuel preheating. In the CPO reformer, the required additional air was supplied by a small pump. No fuel compressor was used as it was assumed that the fuel was in pressurized condition. The topping cycle in Fig. 2.1 (b) was different from that of Fig. 2.1 (a) where fuel reforming was done in an adiabatic steam reformer (ASR) with anode gas recycling and there were total three heat exchangers for fuel preheating. The bottoming cycle was the same in both the configurations in which usual ST cycle components such as economizer, evaporator, superheater, steam turbine, condenser and deaerator were considered. For almost the same input parameters they obtained higher overall efficiency (63%) and more net power (38.03 MW) for the hybrid plant with CPO reformer as against 61.7% and 36.72 MW of the plant with ASR. Temperature of the off-gases entering the HRSG was higher for the plant with CPO which finally resulted in higher efficiency of the bottoming cycle and also the hybrid plant.



(a)

(b)

Fig. 2.1: Hybrid SOFC–ST plant with (a) CPO reformer and (b) with ASR [49, 50]

In another system configuration [49, 50] with recuperation of HRSG off gases for compressed air preheating (Fig. 2.2), the cycle efficiency increased to 68% and 67.7% respectively for the configuration with CPO and steam reforming respectively. Further it was shown that plant overall efficiency increased to a certain limit with decreasing SOFC fuel utilization.

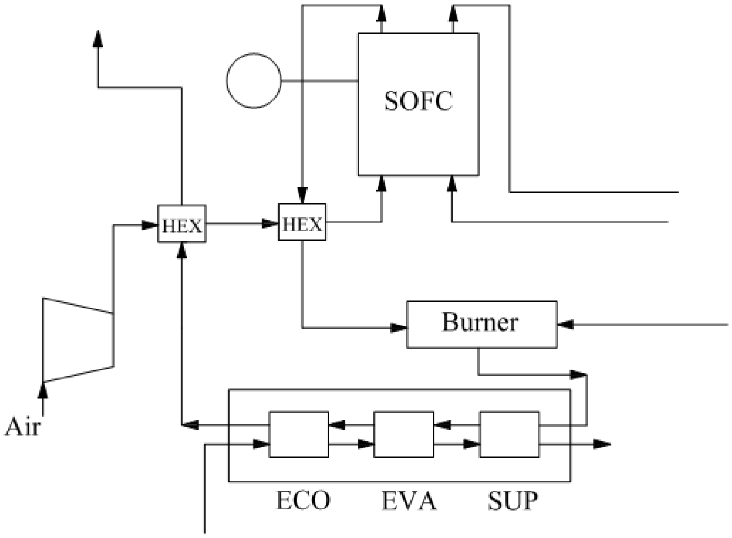


Fig. 2.2: Cathode air preheating by HRSG off gas in SOFC–ST cycle [49, 50]

Rokni [51] in another study carried out a parametric study to investigate the sensitivity of the suggested SOFC–ST plant. It was shown that the operating temperature of the desulfurization unit, pre-reformer and the SOFC anode had no effect on the plant efficiency. However, the cathode temperature had a significant effect on the plant efficiency. In addition, when the SOFC fuel utilization factor was decreased from 0.8 to 0.7, it led to increase of the plant efficiency by about 6%. In the study, an optimal plant efficiency of about 71% was achieved through plant optimization.

2.4 Hybrid SOFC–GT–ST Systems

In SOFC–GT–ST systems, the SOFC is the topping cycle; the GT is the bottoming cycle with respect to the SOFC and the topping cycle with respect to the ST. The GT exhaust flows into the HRSG to produce steam for driving the ST which is then condensed and pumped back to the HRSG to complete the steam cycle. Thermodynamic analysis done on combined SOFC–GT–ST systems are also not many. Higher efficiency can be achieved from SOFC integrated combined cycle (CC) power plants [49, 50].

Yi *et al.* [52] analysed separately, an SOFC integrated GT and an SOFC integrated combined GT–ST power cycle considering use of recuperative heat exchanger as design option in the two cycles. It was found that the SOFC integrated combined GT–ST cycle is more efficient than the SOFC–GT cycle. The optimal efficiencies of the recuperated and non-recuperated systems were found almost the same in both the SOFC–GT and SOFC–GT–ST cycles. However, the peak efficiency pressure ratio of the recuperated system was found significantly lower than that of the non-recuperated system. In the conclusion, they also pointed out the merits and demerits of the recuperated and non-recuperated systems in terms of cost, economics, system development and other associated technical challenges with the use of recuperated system and high pressure operation of the compressor, GT and the SOFC in the non-recuperated system.They used a dual pressure bottoming ST cycle in the SOFC–GT–ST system.

Kuchonthara *et al.* [14] analyzed a hybrid SOFC–GT–ST system along with some other enhanced GT cycles viz. the steam injected gas turbine (STIG) cycle and the humid air turbine (HAT) cycle. In the ST cycle, mainly the heat exchangers and the ST with three pressure levels: high-pressure (HP), intermediate pressure (IP), and low-pressure (LP) were considered. The turbine inlet temperature (TIT) and the pressure ratio were varied to determine their affect on system performance while keeping the pressure and temperature of the ST cycle constant. It was found that the thermal efficiency reduced while the specific work increased with TIT. With pressure ratio however the thermal efficiency increased and the specific work did not change much as in the SOFC–STIG system. The thermal efficiency of the proposed SOFC–GT–ST system was found to be 62.21% and 64.81% corresponding to pressure ratios of 5 and 15 respectively. In their work however, the SOFC, GT and ST power output was not shown separately. In this SOFC–GT–ST configuration [14], the GT exhaust was directly used to generate steam in the HRSG without using air/fuel recuperation. The SOFC was considered to be fully internal reforming type. Moreover, this study was limited only to energetic performance evaluation of the proposed system.The hybrid system considered in [14] is shown below in Fig. 2.3.

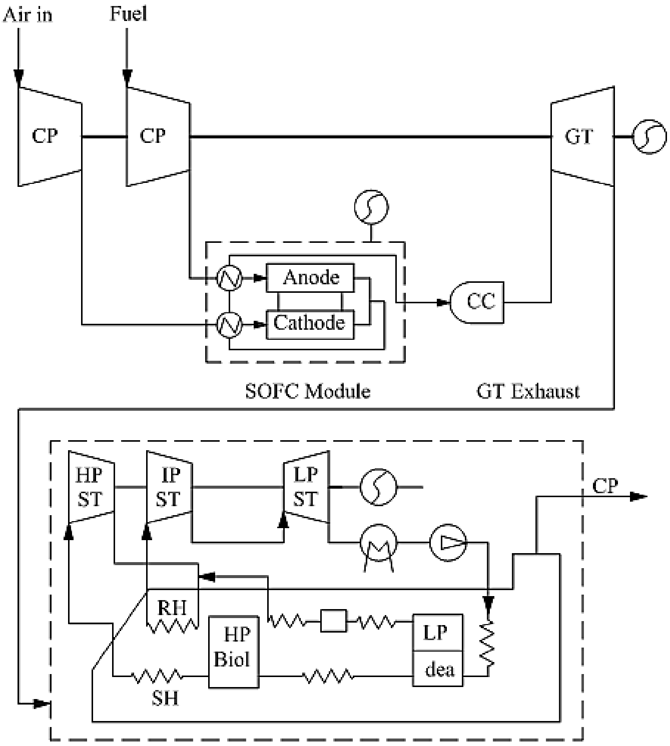


Fig. 2.3: Hybrid SOFC–GT–ST configuration [14]

Arsalis [53] developed a detailed thermodynamic, kinetic, geometric, and cost model analyzing the design and off design operations of hybrid SOFC–GT–ST systems ranging in size from 1.5 to 10 MW. Four different steam turbine cycles viz. (i) a single-pressure, (ii) a dual-pressure, (iii) a triple pressure, and (iv) a triple pressure with reheat were considered. In the thermo-economic analysis, cost functions of different system and component sizes (capacities) were included and analyzed. Finally, the most viable system was obtained through parametric study based on maximizing total system efficiency/minimizing total system life cycle cost. At maximum efficiency of 60.32%, the SOFC, GT and ST power output were shown to be 7.856 MW, 2.310 MW and 1.548 MW respectively. It was observed that the amount of power produced by the GT and ST plant is quite less compared to the SOFC power. The bottoming GT and the ST plant should also produce sufficient amount of power for these to be economically feasible considering high capital/installation cost of these plants. Higher power production from the bottoming GT and ST plant may be possible through additional fuel supply to the afterburner/combustor subject to fulfilling of the maximum TIT criteria (material limit).

In the configuration of Arsalis [53], compressed air preheating and partial fuel reforming in the PR was done by utilizing the heat of combustion gases through anode gas recycling. The combustion gases and the by-passed air stream were mixed and then it was fed into the HRSG for steam generation. There was provision for both fuel and air by-passing the SOFC. A certain amount of fuel was routed directly to the CC by-passing the SOFC. However, there was no provision for fuel preheating in his configuration although fuel preheating is one of the many techniques that can be used for achieving higher efficiency [54]. In his configuration [53] however, a multiple-pressure level (dual pressure/triple pressure/triple pressure with reheat) was used in order to achieve higher power output from the ST plant. Although four different ST cycles were considered in the work by Arsalis [53], but in the results and analysis, it was not clearly explained as to how these bottoming ST cycles (single pressure/dual pressure/triple pressure/triple pressure reheat) affected the power output of the ST cycles or the performance of the overall SOFC–GT–ST system.

In so far as optimization study with SOFC–GT–ST system is concerned, Aminyavari *et al.* [55] performed multi-objective optimization study for an internal-reforming SOFC–GT system integrated with a Rankine (steam) considering the exergetic efficiency and the total plant cost as conflicting objectives. A set of optimal solutions (Pareto front) was obtained and the final optimal design parameters were selected by using the TOPSIS decision-making method.

2.5 Review summary

From the discussion above, it was seen that lot of effort has been made into modeling and analysis of SOFC integrated advanced power cycles. From the review, it could also be found that among the various hybrid SOFC power systems, the SOFC–GT system is the mostly analyzed configuration. Many SOFC–GT configurations have been proposed and investigated till date and scientists are still working on to develop new innovative cycles and design. Moreover, the results obtained from various analyses performed with modeling approach revealed that these results greatly vary with configuration and their operating conditions.

SOFC when integrated directly into a conventional GT cycle leads to performance improvement; both power and efficiency of the hybrid cycle are higher compared to those of conventional cycle without SOFC. SOFC is an efficient electrochemical power conversion device and it performs efficiently at high pressure, hence, a hybrid SOFC–GT system also performs better at high operating pressure. At low pressure operation, the bottoming GT cycle would produce very less power and the system in that case would not be economically feasible.

Fuel reforming is an issue in SOFC which can be done either completely within the fuel cell or partially using an external pre-reformer. For partial external reforming, the source of heat is very crucial and the system would always demand the use of a steam generator even in case of external reforming with anode gas recycling. So SOFC integration would be more appropriate if it is used in combination with GT–ST cycle.

SOFC–STIG is another hybrid cycle that shows superior performance over SOFC–GT system. Direct injection of steam to the combustor helps boosting the net power output and thermal efficiency of a SOFC–GT system.

SOFC–HAT system is another option which can be employed in SOFC hybrid power cycle for further efficiency improvement of the SOFC–GT system. This can be made possible through heat and steam recuperation. Humidified air when enters the SOFC cathode also leads to efficiency improvement of the SOFC.

Majority of the advanced SOFC–GT cycle configurations discussed above have been analyzed based on steady state modeling assumptions. Some of them have dealt with performance evaluation at the design/full load conditions while some others have presented the system performance characteristics at off design/part-load conditions. There have been a number of strategies that have been adopted to achieve the part load/off-design system operation and this is certainly an area where there is possibility of conducting further research.

From the review of analyses done on SOFC–ST and SOFC–GT–ST systems, it was seen that system efficiency in the range of 60-70% is possible from these hybrid configurations. However, not much works on modeling and performance evaluation of hybrid SOFC–ST and SOFC–GT–ST configuration are available. Only a few countable numbers of studies are available on SOFC–GT–ST system analysis and moreover these were specific to energetic performance and cost analysis of the systems at the design and off design conditions. Further in these studies, few certain points were not fully addressed particularly regarding (i) the separate work outputs from the SOFC, GT and ST plants in one and (ii) the effect of integration of bottoming ST cycle of various pressure levels on SOFC–GT–ST system performance in the other. In so far as SOFC–GT–ST systems are concerned, there are not many articles available on system optimization although in some previous studies, the system parameters of a SOFC–GT systems were optimized using optimization techniques such GA, PSO etc. Similarly, inverse analysis has also never been done to estimate parameters of SOFC integrated GT or ST or combined GT–ST power system till now.

2.6 Scope of the present work

In the present study, first a novel hybrid SOFC–GT–ST configuration with single pressure ST cycle is chosen for analysis to evaluate its performance based on variation of its operating parameters but not only from energetic point of view but also to evaluate its exergetic performance. Parametric study evaluating the effect of operating parameters on performance of the individual components and particularly, the bottoming ST plant is important in the sense that effect of these parameters on power output from the bottoming ST plant of a combined SOFC–GT–ST plant has not been comprehensively investigated. Moreover, this has been done for a new SOFC–GT–ST configuration which has the provision for fuel and air preheating utilizing GT exhaust gas, additional fuel burning and steam extraction from the ST for fuel reforming in the pre-reformer (PR). Next, an inverse analysis is carried out for estimating the operating parameters of the proposed SOFC–GT–ST configuration.

In one more attempt, another novel SOFC–GT–ST configuration with triple pressure reheat ST cycle is considered for performance analysis with the help of energy and exergy. The performance of this combined cycle configuration is compared with two other configurations, having dual pressure reheat and single pressure bottoming ST cycles. In this modeling, pinch principle is applied in modeling HRSG of the three bottoming cycles. A detail comparison, both in terms of energy and exergy, is provided along with model formulations of all the three bottoming ST cycles separately.

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